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A review on the methods for biomass to energy conversion systems design

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ABSTRACT

The realization that the level of greenhouse gas (GHG) emissions to the atmosphere is increasing and fossil fuel resources are becoming scarce have increased interest in renewable and sustainable energy systems which use renewable energy sources that are naturally replenished. Production of biofuels from organic material is one of the alternative renewable energy systems. Biofuels can be produced and converted to energy in different kinds of conversion plants with different scales that use various conversion technologies. Before the realization of renewable energy systems investments, carrying out detailed technical and economical feasibility analyses have vital importance. In addition, the most appropriate mix of renewable energy resources and technologies, and optimal plant capacity have to be determined. A well designed energy conversion system can be cost effective, meet economic constraints, use appropriate technologies, has a high reliability and can improve the quality of life. In this regard, various methods can be used to tackle multi dimensionality of the system design problem and the complexity in the technical, economical and social criteria. This study aims to examine the literature on the methods for biomass to energy conversion systems design. To this aim, a comprehensive review is conducted to offer a clear vision of the advances in the field. The studies that are reviewed are classified into three categories; review studies about energy systems, the studies about design of biomass to energy conversion systems and the studies about design of hybrid renewable energy systems that include biomass as an energy source.

Contents

1. Introduction

Sustainable development balances the energy production and consumption with minimal negative impact on the environment. Renewable energy systems as a part of sustainable development bring environmental, energetic and economic benefits such as reduction of GHG, reliable energy supply, economic saving by using natural resources and wastes as feedstock. Although there exist many challenges to assess the feasibility of these systems such as selection of the plant location, optimizing logistical activities, design and sizing of system elements and operational planning, selection of the most feasible combination of units and loadings that will meet a given load demand profile with the specified reliability and considering economical factors would satisfy optimal economic operation of the system.

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Today, biofuels have become a significant alternative source of energy. Biofuels are liquid or gaseous fuels and they originate from biogenic material and include fuels derived from conversion of biodegradable materials called biomass. Compared to most other fuels, the main feature of biofuels is that energy produced through these sources can be renewable. This characteristic of biofuels makes them different from other energy sources commonly used today such as nuclear fuels, coal, and petroleum. Since biofuel production leads to efficient production of energy from organic material, provides recycling of organic wastes and prevents environmental pollution, economic and environmental evaluation of biofuel production has gained importance in recent years. Biofuels are subdivided into two categories, namely "first generation biofuels" and "second generation biofuels". Each of the categories contains a number of different fuels generated from different feedstock. First generation biofuels are made from sugar, starch, or vegetable oil. They differ from second generation biofuels in that their feedstock is not sustainable/green or, if used in large quantity, would have a large impact on the food supply. Some examples of first generation biofuels are bioethanol, biodiesel, vegetable oils like olive oil and sunflower oil, bioethers, biogas and solid biofuels like wood, manure and seeds. Second generation biofuels are made from sustainable/green feedstock such as algae, wood or grass. Cellulosic ethanol, algae-based biofuels, biohydrogen, methanol are some examples of second generation biofuels.

Biofuels can be used for generating centralized as well as decentralized heat, electricity and energy. Globally, biofuels are used for the following purposes: cooking and heating (residential), generating electricity, agricultural uses and fuel additives.

Considering the fact that the number of researches on the design of biomass to energy conversion systems are continuously increasing, this study attempts to provide an updated and comprehensive survey in this field. This paper is further organized as follows. Sections 2 to 4 present the review studies about energy systems, the studies about design of biomass to energy conversion systems and the studies about design of hybrid renewable energy systems including biomass as an energy source, respectively. As "technology and process selection", "configuration design and sizing" and "capacity sizing" are three important phases of the system design procedure, they are considered in classification of the studies in the field. Finally, concluding remarks are presented in Section 5.

2. Review studies about energy systems

Since energy planning problems include multiple decision makers, multiple conflicting criteria, many sources of uncertainty, long time frames and capital-intensive investment structures [2], decision making in such problems requires selection of the suitable methods as in many complex planning problems. In this section, pioneer review studies about decision making in energy planning problems are surveyed.

Bazmi et al. [1] reviewed the literature on power and supply sector developments and analyzed the role of modeling and optimization in this sector. They discussed the current state of power generation technologies and also reviewed the researches about decentralized electricity systems. Løken [2] provided a brief overview of three classes of multi-criteria decision making (MCDM) methods. Huang et al. [3] conducted a literature review on decision analysis in energy and environmental modeling. In addition, Zhou et al. [4] updated and extended the Huang et al.'s [3] survey.

Pohekar and Ramachandran [5] analyzed the applicability of various MCDM methods to sustainable energy planning in their review. After giving an overview of some MCDM methods, they presented applications of MCDM methods, multi-objective optimization and decision support systems in energy planning. Wang et al. [6] conducted a review on multi-criteria decision analysis aid in sustainable energy decision-making. Banos et al. [7] presented a review of the current optimization methods for design, planning and control problems in the field of renewable and sustainable energy, and briefly overviewed single and multi-objective optimization (MOO). According to Buchholz et al. [8], a complete bioenergy system includes feedstock production, conversion technology and energy allocation components, and multi-criteria analysis (MCA) can assist in structuring the problem. In this concern, they evaluated the potential of MCA to facilitate the design and implementation of sustainable bioenergy projects.

Anaerobic Digestion (AD) is a chain of interconnected biological reactions, where the organic matter is transformed into methane, carbon dioxide and anaerobic biomass, in an oxygen-free environment. The complexity of designing and management of such biological systems involving various bacterial populations and substrates increases the need for detailed analysis. Donoso-Bravo et al. [9] reviewed modeling frameworks in the field of anaerobic digestion processes. They discussed various optimization techniques for parameter estimation, and parameter uncertainty estimation methods in detail. Igoni et al. [10] provided a synthesis of the key issues and analyses concerning the design of a high performance anaerobic digester for producing biogas from municipal solid waste. They classified digester design considerations in 11 classes. Appels et al. [11] presented a detailed review about the principles of anaerobic digestion, process parameters, design methods and criteria, the biogas utilization and the potential problems. Ward et al. [12] conducted a review on optimization of anaerobic digestion of agricultural resources. They examined the basic reactor design considerations, the features of mixing regime, environmental conditions, various types of feedstocks, effects of co-digestion, pre-treatments and additives, monitoring of digestion process and control systems. Karellas et al. [13] gave a brief overview about anaerobic digestion/reactor technology according to different feedstocks and developed an investment decision tool to evaluate the biogas production economically. In the study, the biogas production was estimated with the use of the tool for an anaerobic digestion plant where three organic feedstocks are utilized.

3. Studies about design of biomass to energy conversion systems

Biomass has a great potential as a renewable feedstock for producing various energy forms. However, in order to compete with fossil energy sources efficient conversion technologies need to be utilized. Among all the options given for a defined system components and power generation, not all combinations may be sensible from efficiency and economic point of view. Therefore, selecting appropriate process configurations that leads to optimal plant design constitutes an important part of this study.

Besides determining the optimal configuration and equipment sizing, it has a vital importance to decide the optimal production capacity, size and scale of the plant. A trade-off between centralized large plants and distributed small plants is required before making installation decisions. In this regard, several studies considering technical, economic and environmental criteria are conducted.

In this section some of the pioneer studies about design of biomass to energy conversion systems are reviewed. Considering the problem type handled, the studies are subdivided into three categories; studies about "technology and process selection",

studies about “configuration design and sizing” and studies about “capacity sizing”.

3.1. Technology/process comparison and selection

Biomass can be converted into useful forms of energy with a wide range of technology and process options. Conversion of biomass to energy is undertaken using three main process technologies: thermo-chemical, bio-chemical/biological and mechanical extraction. Within thermo-chemical conversion, four process options are available; combustion, pyrolysis, gasification and liquefaction. In addition, bio-chemical conversion encompasses two process options; digestion and fermentation [14].

Different process types for conversion of biomass have been studied by a number of researchers in recent years. Among these studies, McKendry [14] presented a brief review of the main conversion processes. Having investigated the different thermo-chemical and bio-chemical conversion process options, they found that only gasification is likely to be commercially viable. Demirbas [15] reviewed the biorenewable fuel valorization facilities as well as the future importance and upgrading concepts of biorefineries. The author also reviewed the types of biofuels and biofuel feedstocks, thermochemical and biochemical conversion processes of biorenewables, Fischer–Tropsch Synthesis of syngas from biorenewables. Nichols [16] assessed anaerobic digestion systems processing source separated organics or municipal solid waste as part of a feasibility study for Seattle. Faaij [17] gave an in depth overview of the state-of-the-art of key biomass conversion technologies and technologies that may play a key role in the future, products of the conversion processes and markets for bio-energy. Puig-Arnavat et al. [18] presented a review that aims to analyze and compare different types of gasification models. Peterson and Haase [19] prepared an exhaustive report to assess the market of small and medium scale biomass gasification and combustion technology. The assessment provides an overview of solid biomass resources available in the United States, description and discussion of gasification and combustion conversion technologies that utilize solid biomass. Damartzis and Zabaniotou [20] presented the main processing steps for the biomass conversion technology. They also investigated process modeling studies and optimization approaches for the determination of the optimal operating range of each processing step. Additionally, Stanford University Global Climate and Energy Project Team [21] proposed a technical report on assessment of biomass feedstock and conversion research opportunities. Diya'uddeen et al. [22] presented a review to give an overview of potential industrial, agricultural and municipal sources of feedstock for biodiesel production. Properties of used domestic waste oil as biodiesel feedstock and production of biodiesel from used domestic waste oil are dwelt on. Quality of fuel, performance of the system and the benefits of using used domestic waste oils as a fuel source are further discussed in the study. Hill [23] conducted a review study to explore the environmental costs and benefits of producing crops as feedstock for biofuel production industry. The author compared the benefits of crop cultivation for biofuel production and for food and also investigated the advantages of second generation transportation biofuels over the first generation food-based biofuels. The study reveals the current state and impacts of increasing of biofuel production in United States and alternative biofuel feedstock production methods.

Münster and Lund [24] compared eight different waste-to-energy technologies in three different scenarios. The comparison was carried out by EnergyPLAN model that is developed at Aalborg University. The model assists energy planning strategies on the basis of technical and economic analyses. Searcy and Flynn [25] evaluated four different processing technologies which differ in the capital cost per unit of biomass processed. A model was developed in the study to calculate the total of biomass processing cost, field cost and transportation cost. In their subsequent study [26], the researchers suggested a criterion as the most appreciate social criterion for making the best choice among various technology alternatives, the minimum incremental cost per unit reduction in GHG emissions. In another study, Cameron et al. [27] stated that for a given source of biomass, three factors have a strong impact on the cost of biomass utilization; the end product, the conversion technology and the scale of the plant. In the study, they considered only electrical power as the end product and evaluated the impact of feedstock cost on technology selection and optimum plant size with comparing two conversion technologies. Karagiannidis and Perkoulidis [28] developed a conceptual framework and methodological tool for evaluating, comparing and ranking five different AD process technologies suitable for treating the organic fraction of municipal solid waste. Dolan et al. [29] presented a model to calculate internal rate of return for the financial appraisal of a wet mesophilic AD plant. The model identifies the most financially viable configuration of AD technology based on six scenarios.

El-Mashad et al. [30] advocated that temperature is an important factor that may affect the performance of anaerobic digestion, and that solar energy or another renewable source to heat the reactor is a good and environment friendly alternative. They studied on incorporation of solar heating systems into anaerobic reactors. Kazi et al. [31] conducted a techno-economic study that compares several process technologies for the production of ethanol. With the aim of examining the short-term commercial viability of biochemical ethanol production, seven process scenarios were included in the analysis. Anex et al. [32] made a techno-economic comparison based on capital and operating costs, energy efficiency and product value for six biomass-to-liquid fuels technology scenarios representing three conversion platforms; pyrolysis, gasification and biochemical. Keirstead et al. [33] stated that urban biomass energy systems pose a number of practical challenges including the use of specialist technologies, a range of alternative supply chains and local air pollution impacts. They developed an optimization model to select among alternative conversion technology options to identify an optimal urban biomass energy system.

Piccolo and Bezzo [34] stated that ethanol is one of the most promising biofuels, as it can be derived from any material containing simple or complex sugars. They analyzed and assessed two different process options for production of fuel ethanol from lignocellulosic feedstock.

Sharmaa et al. [35] proposed a mixed integer linear programming (MILP) model for technology and product portfolio design for a multi product multi platform biorefinery. A preliminary process design and product portfolio is provided. Nawaz et al. [36] and Zondervana et al. [37] proposed a biorefinery optimization model that can be used to find the optimal processing route for the production. They developed a mixed integer nonlinear programming (MINLP) model to determine the optimal processing routes.

Tock et al. [38] presented a systematic methodology that consists of energetic and economic models to analyze and evaluate technological process alternatives for thermochemical conversion of biomass into different types of liquid fuels. A thermodynamic model, energy-flow models and energy-integration model were used in the study to predict the thermodynamic, economic and energetic performances of the process to identify promising system configurations that constitutes the preliminary design of the optimal plant.

Municipal solid waste management was also investigated by a number of researchers. Hokkanen and Salminen [39] studied on choosing a solid waste management system using multi-criteria decision analysis. Murphy and McKeogh [40] studied on technical,

economic and environmental analysis of energy production from municipal solid waste. Four technologies that produce energy from municipal solid waste were investigated in the study. Murphy and Power [41] conducted a study on technical, economic and environmental analysis of energy production from newspaper in Ireland. In this regard, they compared four scenarios. Vego et al. [42] presented an application of MCDM in strategic municipal solid waste management in Dalmatia, Croatia.

Cogeneration is the combined production of two forms of energy—electrical or mechanical power plus useful thermal energy—in one technological process and from a single fuel source. Since cogenerators produce two forms of energy in one process, they will provide substantial energy savings relative to conventional separate electric and thermal energy production technologies [43]. One of the main components of biomass to energy conversion plants is CHP unit that converts the biogas to energy.

Raj et al. [43] presented a detailed literature survey of cogeneration technologies based on renewable energy sources. Related technologies were classified in the study based on design, modeling and simulation, environmental issues and energy policies. Yilmaz [44] conducted a performance analysis based on alternative performance criteria to determine the optimum values of the design parameters of a cogeneration cycle. Henning [45] described an energy system optimization model called MODEST that may be used to decide which investments to make and dimensioning of the new installations. MODEST uses linear programming (LP) to minimize the costs of energy supply and demand-side management. Pilavachi et al. [46] evaluated different CHP options using various criteria by a multi-criteria method. Seven criteria were used to assess the sustainability of 16 CHP technology alternatives. Dinca et al. [47] analyzed seven heat and power generation scenarios based on natural gas in terms of ecological, energetical, economic and technical criteria. Six CHP and one separate generation technology alternative were evaluated in the study. Alanne et al. [48] compared a fuel cell micro-CHP heating system with traditional heating alternatives for a single-family house in Finland to select a residential energy supply system. Fragaki et al. [49] investigated the economics and optimum design of combined heat and power plants with gas engines and thermal stores in United Kingdom market conditions. According to Marechal and Kalitventzeff [50], the need to satisfy the energy requirement of a process at minimum cost makes the “Minimum Energy Requirement” concept a key issue of energy-integration studies. They presented a systematic methodology that consists of three steps to determine the optimal CHP configuration.

Ren et al. [51] developed a MINLP model to design energy systems for a given residential customer equipped with a CHP plant which is driven by natural gas and includes a storage tank and a back-up boiler. The model reports the optimal CHP system capacity. Beihong and Weiding [52] proposed an optimal planning methodology for the sizing problem of cogeneration systems. The methodology determines the optimal equipment capacities to the objective of minimizing annual total cost. Six case studies were evaluated and compared in the study. Oh et al. [53] used an MILP model to obtain optimal system configuration in terms of size and number of equipments, and optimal operational strategy in terms of on/off status of system components.

Energy demand estimated at the planning stage has a certain degree of uncertainty. Hence, if the system is designed treating energy demand as certain variable, economic, technical and energetic properties estimated at the planning stage may not be achieved at the operation stage. Emphasizing this problem, Gamou et al. [54] proposed an optimization methodology for unit sizing of cogeneration systems taking into account uncertainty of energy demand by using continuous random variables to represent the demand. With the methodology, system design variables like equipment capacities and operational strategies were determined.

The recent advances address the exploitation of excess heat produced by CHP systems by converting it to cooling power that can be used in different industrial or domestic activities such as air conditioning. This is known as trigeneration or combined cooling, heating and power (CCHP) plants and is becoming economically viable by the commercial spread of absorption chillers.

Considering that the technical, economical, environmental and energetic performances of a CCHP system are closely dependent on its design and operation strategy, Wang et al. [55] evaluated the performance of CCHP systems considering primary energy saving, annual total cost saving and CO_2 emission reduction criteria. In addition, Kavvadias et al. [56] proposed a methodology for designing a trigeneration plant by considering various operation parameters. They introduced a new operation strategy that can be an alternative to the most common operation strategies of trigeneration systems. Arcuri et al. [57] presented a procedure to solve optimally the sizing and operational planning problem of a trigeneration system. Cardona and Piacentino [58] developed an original methodology for the choice and management of trigeneration plants. Aggregate thermal and cooling demands including direct heat consumption in winter and absorber feeding consumption were calculated, and additionally relative cumulative curves were obtained in the study. Based on these data, the prime mover and absorption chiller sizes were selected. The methodology was illustrated with an application in hotel sector. Kong et al. [59] developed an LP model to determine the optimal energy combination and operation management strategy to fulfill the energy demand with minimum overall cost of energy for the CCHP system. Mago and Chamra [60] state that CCHP systems analyses are frequently based on operating costs but these systems can be optimized based on different optimization criteria such as actual energy savings or minimum environmental impact beside reduction of costs. In this regard, they developed an optimization procedure to evaluate and optimize CCHP systems. Cho et al. [61] state that design of CHP and CCHP systems involves selection of type and size of system components, and component efficiencies, system operating mode and energy demand must be taken into consideration in the selection process. The researchers presented an optimization procedure for the CCHP systems operation in different climate conditions.

Lai and Hui [62] emphasized that the system should be feasible and flexible to overcome demand variations. They discussed over-sizing, thermal storage and re-allocation concepts for a tri-generation system to overcome the seasonal and daily demand variations with a feasible and flexible system design.

3.2. Configuration design and sizing

Some researchers dealt with the biomass to energy conversion system design problem handling the system as a whole, as design configurations that consists of different technology and equipment options.

Hamelinck et al. [63] analyzed the system components necessary for diesel production from biomass, and determined the promising conversion configurations. They investigated the technical and economic performances of the process with a dynamic model to evaluate the influence of each parameter or device on investment costs, fuel and electricity efficiency and diesel product costs.

Arena et al. [64] focused on the biomass gasification process. They evaluated and compared the most promising design configurations for small-scale industrial applications. Different analytical tools were used to analyze the experimental data such as mass and energy balances and material and substance flow analyses. Jurado

et al. [65] developed a detailed modeling of a combined cycle power plant which consists of a gas turbine, a heat recovery steam generator and a steam turbine. Process and performance information of a biomass gasifier-based power station was simulated in the study by using MATLAB. Ren et al. [66] developed an LP model in order to aid the design and evaluation of a biomass CCHP plant. The model reports the optimal biomass energy system capacities to meet the customers' electrical and thermal energy demands economically. Van den Enden and Lora [67] proposed a design approach for a biomass fed fluidized bed gasifier using comprehensive simulator for fluidized bed equipment (CSFB). After a preliminary sizing is carried out to estimate the main design dimensions and operational parameters, the question rise about whether the preliminary design will give an optimal performance is answered in the study. Raheman [68] developed an LP model for determining the component dimensions of a fixed dome type Deenbandhu model biogas plant, the most popular model constructed in India. Singh et al. [69] described a non-linear programming (NLP) model of an unheated biogas plant that can be used to predict biogas generation at any given geographical location. The other aim of the study is to optimize the retention time and size of the biogas plant for a given daily biogas requirement with the help of economic analysis.

Giarola et al. [70] presented an MILP framework to optimize the environmental and financial performances of bioethanol supply chains simultaneously. They aimed to determine the optimal system configuration that maximizes the financial profitability while minimizing the GHG emissions. Corsano et al. [71] developed a MINLP model for the simultaneous optimization of a bioethanol supply chain and plant design to determine the configuration of plants, and the unit sizes.

Fazlollahi and Marechal [72] stated that the energy system analyses can be divided into two main steps; “sizing and design optimization” and “operation optimization”. Integration of the simulation models of biomass technologies and MOO for sizing and designing a cogeneration plant were combined in the study in a systematic way. Multi-objective evolutionary algorithms and MILP were used to simultaneously minimize costs and meet environmental requirements. Maréchal et al. [73] described a methodology for the design of fuel cell systems combining process integration, process simulation and modeling and MOO techniques. The method was used to determine promising system configurations. A thermo-economic performance model of the superstructure that includes an energy-flow model is developed. Gassner and Maréchal conducted a series of research that dealt with the design of thermo-chemical fuel production plants. In one of these studies [74], they presented a methodology for the optimal design of thermo-chemical biofuel production processes from biomass. The methodology consists of an energy-flow model to determine the heat transfers and power requirements of the equipments, an energy-integration model to calculate the energy conversion and heat transfer, an economic model and a MOO model. Using the results of the energy-flow and integration steps as the equipment design targets, optimal design configurations were generated with MOO. The researchers applied the method for thermo-chemical production of synthetic natural gas (SNG) from lignocellulosic biomass in their subsequent study [75]. Different technological alternatives for different production steps were identified and evaluated in the study to determine suitable configuration for the process.

Gerber, Gassner and Maréchal conducted studies that take into account environmental impacts of the biomass to energy conversion systems as a criterion in addition to economic and thermodynamic criteria for the system design and optimization. In this regard, they studied on the integration of life cycle assessment (LCA) in the models to design energy conversion systems. Gerber et al. [76] developed a methodology to integrate process design with LCA. Their methodology is based on the thermo-economic design approach described by Gassner and Maréchal [75]. For this purpose, the life cycle inventory, which is an inventory of flows from and to nature, is mathematically expressed as functions of decision variables of the thermo-economic model. Life cycle impact assessment was used in the study to obtain environmental indicators, and these indicators were adapted to process design and scale. The researchers extended the research in their subsequent studies, Gerber et al. [77,78]. By using LCA, they discussed strategies for the environmental-economic optimization of renewable energy conversion technologies that are at the conceptual process design stage and produce multiple energy services. Investigating optimal process scale with respect to SNG production costs and environmental impacts is one of the main purposes of these studies.

Brown et al. [79] defined a MOO problem for thermo-economic analysis of biomass gasification systems-based on a superstructure of alternative configurations for energy-flow for each processing step. The selection of processing units and operating conditions was investigated in the study. Process equipment cost and sizing parameters were taken as functions of gasification operating conditions. The design problem was solved with a MOO evolutionary algorithm.

3.3. Capacity planning

Planning system size, scale and capacity constitute an important part of the design problem besides of the evaluation of technology, process and configuration options for energy systems.

Jenkins [80] proposed a set of NLP formulations to determine the optimum size of a biomass utilization facility subject to an economy of scale in capital and operating costs. Optimum capacity of the facility and output production cost associated to that capacity were determined according to two different assumptions; the scale is constant and the scale is variable. Grado and Chandra [81] proved that the size of manufacturing facility has the biggest impact on total cost variability. They performed a sensitivity analyses based on factorial design to compare the relative influence of various model parameters on the production cost. The impacts of the main factors on the production system were evaluated in the research. Fiala et al. [82] identified and tested a model to identify the feasibility of biomass energy systems. The model was developed to determine the optimum electric power output and number and size of the plants to be installed in a given agricultural area.

Unpredictable factors play an important role when utilizing natural sources as renewable energy sources. In view of this fact, D'Ovidio and Pagano [83] took into account the stochastic nature of uncertainty and extended the deterministic approach proposed by Fiala et al. [82] by characterizing uncertainty introducing a probabilistic approach. A stochastic MCDM tool was developed in the study. In addition, a comparison between conversion process technologies was made by using MCDM. Monte Carlo simulation was employed in the study for the numerical applications. Walla and Schneeberger [84] investigated the relationships between the costs of biogas and electricity production from maize silage. They derived a relationship between the capacity of a CHP unit and its electrical efficiency. Then they developed a model to investigate unit costs of biogas and electricity production and transportation costs for feedstock and biogas slurry in relation to plant size. Sultana et al. [85] developed a techno-economic model for estimation of the cost of producing pellets and optimum size of the pellet production plants.

Amigun and Blottnitz [86] emphasize that biogas technology is a promising energy system for low population and remotely

situated communities in view of the fact that implementation of centralized energy generation and distribution systems are prohibitively costly and inefficient. The researchers investigated the significance of plant capacity and plant location on the capital investment cost of African biogas plants. They derived plant capacity, geographical location and cost information of 38 biogas installations from 12 African countries.

Kim et al. [87] formulated a MILP model to decide the optimal number, locations and sizes of various types of biofuel processing plants. In addition, the amount of biomass and final products transported between the selected locations over a time period were determined to maximize the overall profit. The researchers [88] improved their model by considering the uncertainties in the model parameters. They computed the impact of each uncertain parameter on the objective function for each end of the parameters' range. Leboreiro and Hilaly [89] developed a model to evaluate biomass collection, transportation costs, and optimum plant size of biorefineries. Akgül et al. [90] developed an optimization framework for a bioethanol supply chain network to determine locations and scales of biofuel production facilities. Marvin et al. [91] used MILP to determine the place and capacity of biorefineries, the amount of biomass to harvest and biorefineries that the harvested biomass transported to.

Besides the economic point of view, it has a vital importance to evaluate the environmental feasibility of producing energy from biomass. In this regard, Tan et al. [92] presented a fuzzy multi-objective modeling framework based on a linear input–output life cycle model that includes material and energy balances for determining optimal bioenergy system configuration. Frombo et al. [93] developed a geographic information system (GIS)-based environmental decision support system (EDSS) for the optimal use of wood biomass for energy production and the optimal selection of plant size, location and technology.

Table 1 reports the methods employed in the studies about biomass to energy conversion plant design that are reviewed in this work.

4. Review on the studies about design of hybrid renewable energy systems including biomass conversion

An energy system that uses two or more different kinds of renewable energy sources is called hybrid renewable energy system. These systems use renewable energy sources together and provide energy supply in a more economic, environment friendly and reliable manner than systems using single source. Renewable energy resources can be integrated into energy systems by considering economic, technical, social or operational objectives and different criteria sets. In this regard, Ostergaard [94] investigated a series of optimization criteria for the design of renewable energy systems.

Optimal design of hybrid energy systems is a complex task because of the randomized nature of alternative energy sources, electrical load profile and the non-linear response of system components. To address this problem, Luna-Rubio et al. [95] presented a brief overview about the optimal sizing methodologies for hybrid renewable energy systems. They reviewed the hybrid energy metrics and assessed the sizing methods. Erdinc and Uzunoglu [96] also provided a detailed review of hybrid renewable energy system sizing approaches in literature. Commercially available software tools and heuristic optimization techniques are overviewed in the study. Additionally, Connolly et al. [97] reviewed different computer tools that can be used to analyze the integration of renewable energy.

The main problem about renewable energy sources is that they are highly dependent on environmental conditions and naturally variable. Biomass energy systems can be a complementary system taking into account their different properties in reliability when compared to other renewable energy systems such as wind or solar energy systems. For a successful integration, it is worthy to analyze in detail the capabilities of the integrated systems. In this regard, Perez-Navarro et al. [98] dealt with the reliability problem of a wind energy system arise from natural variability of the wind resource. They proposed a methodology to design the main parameters of a hybrid system that includes a biomass gasification power plant, a gas storage system and stand-by generators to stabilize a wind park. Hakimi and Moghaddas-Tafreshi [99] also studied on the integration of biomass and wind energy systems. They developed a method that can be applied to optimal sizing and operation strategy of a hybrid power system meeting residential area energy demand.

Gupta et al. proposed a tri-series paper about modeling of a hybrid energy generation system consisting of a photovoltaic array, biomass, biogas, small/micro-hydro, a battery bank and a fossil fuel generator. The first paper of the series [100] developed a MILP model of the system to determine the sizes of sub-systems and optimal operation strategy. In the second paper [101], they presented a combined dispatch strategy-based solution algorithm to determine the optimal operation strategy and optimal sizing for a hybrid system by using the models for various components developed in the first paper. The third paper [102] presented the results of the application of MILP model developed in the first paper. It also presented the simulation algorithm developed in the second paper for determining sub-system sizes and operational/dispatch strategy economically to supply the load of a rural remote area in Uttarakhand state, India.

Kanase-Patil et al. presented three papers about optimizing the integrated renewable energy systems for rural electrification of seven remote villages. In the first paper [103], they proposed the off grid electrification by utilizing integrated renewable energy system based on LP approach to satisfy the electrical and cooking needs of the villages. Four different renewable energy scenarios were considered in the paper during modeling and optimization process. In their second paper, [104] they developed an Integrated Renewable Energy Optimization Model (IREOM) that consists of locally available renewable energy sources to meet energy demands of the cluster of the villages. Their study includes the selection and sizing of different system components for given seasonal load profiles and site specific conditions for renewable energy resources. The third paper [105] is an extension of the formers and presents the comparative study of manufacturer-specified and user-specified sizes of renewable energy systems by considering seasonally varying load profile of the area. Details of the mathematical models of these renewable energy systems were reported in their earlier publications [106–110]. The model suggests the least expensive system configuration and determines the sizes of renewable energy systems for the required reliability level.

Rubio-Maya et al. [111] developed a new systematic selection and sizing procedure for a polygeneration plant fueled by natural gas, solar energy and gasified biomass. They presented a two-level optimization procedure that consists of synthesis of different system components and preliminary design as the first-level and a detailed design and plant operation as the second-level. In the first-level, an optimization process was designed to select the technically feasible configurations and the preliminary design capacities of main devices are estimated. The second-level was described by Rubio-Maya et al. [112]. Output from the first-level constitutes the starting point of the second-level that optimizes the plant operation and definite design of the plant. Although only monthly averaged data requirements were considered at the first-level, the second-level includes a detailed modeling of pre-selected devices with daily load variability.

Table 1
The methods employed in the studies about biomass to energy conversion plant design.

Reference	Methodology	Reference	Methodology
Münster and Lund [24]	EnergyPLAN model	Mago and Chamra [60]	Multi-objective NLP, simulation
Searcy and Flynn [25]	Graphical evaluation	Cho et al. [61]	Multi-objective NLP, simulation
Searcy and Flynn [26]	Graphical evaluation	Lai and Hui [62]	Graphical feasible region analysis, cost analysis
Cameron et al. [27]	Graphical evaluation and comparison, cost analysis	Hamelinck et al. [63]	Technical analysis with AspenPLUS process simulator, economic analysis, cost analysis
Karagiannidis and Perkoulidis [28]	ELECTRE III (MCDM)	Arena et al. [64]	Analytical tools such as mass and energy balances, material and substance flow analysis
Dolan et al. [29]	Economic evaluation with IRR method	Jurado et al. [65]	Simulation
El-Mashad et al. [30]	NLP, simulation	Ren et al. [66]	LP, sensitivity analysis
Kazi et al. [31]	Simulation	Van den Enden and Lora [67]	Simulation
Anex et al. [32]	Cost analysis	Raheman [68]	LP
Keirstead et al. [33]	MILP based resource-technology network	Singh et al. [69]	NLP, prediction-curve fitting of laboratory data/least square method with saturation growth rate model, economic analysis -life cycle cost analysis
Piccolo and Bezzo [34]	Simulation, optimization with Pinch Technology Analysis, sensitivity analysis, financial evaluation with payback analysis	Giarola et al. [70]	MILP
Sharmaa et al. [35]	MILP	Corsano et al. [71]	MINLP
Nawaz et al. [36]	MINLP	Fazlollahi and Marechal [72]	MINLP, evolutionary MOO, thermo-economic simulation, multi-period energy-integration model based on MILP
Zondervana et al. [37]	MINLP	Marechal et al. [73]	MINLP, MOO, sizing, costing and transfer between modeling steps with a MATLAB based interface
Tock et al. [38]	NLP, graphical evaluation, sensitivity analysis	Gassner and Maréchal [74]	MOO
Hokkanen and Salminen [39]	ELECTRE III (MCDM)	Gassner and Maréchal [75]	MOO
Murphy and McKeogh [40]	Scenario analysis	Gerber et al. [76]	LCA, simulation, trade-off analysis, MOO
Murphy and Power [41]	Scenario analysis	Gerber et al. [77]	LCA, simulation, trade-off analysis, MOO
Vego et al. [42]	PROMETHEE and GAIA (MCDM)	Gerber et al. [78]	LCA, simulation, trade-off analysis, MOO
Yilmaz [44]	Mathematical analysis including thermodynamic equations, energy utilization, thermal efficiency, energy efficiency	Brown et al. [79]	Configuration superstructure simulation, evolutionary MOO
Henning [45]	LP	Jenkins [80]	NLP, sensitivity analysis
Pilavachi et al. [46]	A MCDM method with an agglomeration function	Grado and Chandra [81]	Sensitivity analysis based on factorial design
Dinca et al. [47]	A NAIDE-based method (MCDM)	Fiala et al. [82]	NLP, sensitivity analysis
Alanne et al. [48]	PAIRS method (MCDM)	D'Ovidio and Pagano [83]	Stochastic MCDM, Monte Carlo simulation
Fragaki et al. [49]	Economic analysis with net present value (NPV), sensitivity analysis	Walla and Schneeberger [84]	Regression analysis, sensitivity analysis, cost curves
Marechal and Kalitventzeff [50]	Combined use of MILP and an expert system, sensitivity analysis, break even analysis	Sultana et al. [85]	Cost curves, sensitivity analysis
Ren et al. [51]	MINLP, sensitivity analysis	Amigun and Blottnitz [86]	Curve fitting, least square method, regression/correlation analysis
Oh et al. [53]	MILP	Kim et al. [87]	MILP
Gamou et al. [54]	Enumeration method in MILP, sensitivity analysis	Kim et al. [88]	MILP, sensitivity analysis
Wang et al. [55]	NLP, MODM, genetic algorithm, sensitivity analysis	Leboreiro and Hilaly [89]	NLP, graphical analysis, sensitivity analysis
Kavvadias et al. [56]	Simulation, graphical analysis, sensitivity analysis	Akgül et al. [90]	MILP
Arcuri et al. [57]	MIP, economic analysis with NPV	Marvin et al. [91]	MILP
Cardona and Piacentino [58]	NLP, cumulative curves	Tan et al. [92]	Fuzzy multiple-objective modeling framework based on a linear input-output life cycle model
Kong et al. [59]	LP	Frombo et al. [93]	A GIS based EDSS based on MINLP optimization model

Zhou et al. [113] presented an energy systems engineering framework towards the optimal design of distributed energy systems with the purpose of obtaining optimal combination of technologies and capacity of equipment for a given area with given energy demands. The framework includes six primary energy resources, namely natural gas, diesel, wind, solar energy, biomass and geothermal. The framework consists of a superstructure-based model, featuring simultaneous determination of the optimal configuration and its optimal operating conditions via MILP.

In rural areas, electrification based on local agricultural wastes and forest biomass is a more suitable alternative to overcome the difficulties arise from low population densities, highly dispersed location of populated centers and low energy consumption. Herran and Nakata [114,115] studied on designing decentralized energy systems for rural electrification by using local biomass resources in rural areas of developing countries. Herran and Nakata [114] introduced an LP model to evaluate and design a decentralized energy system for rural electrification in developing countries using local biomass resources. The aim of the model was to find the most suitable combination of energy resources and conversion technologies to meet demand of the target area. The extension of the LP model was presented by Herran and Nakata [115]. By the study, they arrived at a more comprehensive outlook of decentralized electrification. Herein, optimal designs of the energy system for the considered scenarios were provided. The results showed that transportation distances and efficiencies of biomass conversion technologies have significant impact on system configuration and performance. Nakata et al. [116] used optimization modeling to integrate renewable energy systems, namely wind, photovoltaic and biomass systems, to provide electricity and heat in rural Japan. The model provides the least cost system configuration by optimizing the capacities of the components and the system operation considering hour-by-hour energy availability and demand.

San Cristóbal [117] emphasized that multiple conflicting objectives and factors that affect the success of a renewable energy project must be analyzed and taken into account. Additionally, they stated that complex social, economic, technological and environmental factors of such projects make multi-criteria analyses a valuable tool for decision making about renewable energy planning. In the study, compromise ranking method (VIKOR method) was combined with Analytic Hierarchy Process (AHP) for weighting the importance of different criteria. They illustrated the application of the method with the aim to select among 13 different renewable energy alternatives according to seven different criteria. Kahraman and Kaya [118] suggested a fuzzy MCDM methodology stating that the fuzzy set theory is a powerful tool to deal with uncertainty in the case of incomplete or vague information. The proposed methodology was applied to determine the most appropriate energy policy for Turkey considering miscellaneous energy alternatives. In the selection process 4 main criteria and 17 sub-criteria were considered.

Table 2 reports the methods for designing hybrid renewable energy systems including biomass conversion.

Table 2
The methods for designing hybrid renewable energy systems including biomass conversion.

Reference	Methodology
Perez-Navarro et al. [98]	NLP, simulation
Hakimi and Moghaddas-Tafreshi [99]	Simulation
Gupta et al. [100]	MILP
Gupta et al. [101]	Simulation
Gupta et al. [102]	MILP, simulation
Kanase-Patil et al. [103–110]	LP
Rubio-Maya et al. [111,112]	LP
Zhou et al. [113]	Superstructure-based modeling, MILP
Herran and Nakata [114]	LP
Herran and Nakata [115]	LP, sensitivity analysis
Nakata et al. [116]	NLP
San Cristóbal [117]	MCDM with VIKOR and AHP combination
Kahraman and Kaya [118]	Fuzzy AHP

5. Conclusions

Renewable energy systems are alternative energy production systems to overcome the problems caused by today's commonly used energy sources such as nuclear fuels, coal, and petroleum. Major advantages with the use of renewable energy are that as it is sustainable and will never run out and produces little or no waste such as carbon dioxide or other chemical pollutants, so has minimal impact on the environment and atmosphere. To be competitive with fossil fuel resourced energy systems, renewable energy systems must be well designed in terms of technical, economical, environmental and social criteria.

As a worldwide used renewable energy system type, biomasses to energy conversion systems are dealt within this study. Review, evaluation and selection studies about biomass to energy conversion technologies indicate that the implementation of the process is technically feasible by means of well developed basic principles although some challenges can be encountered related to economical and operational considerations. Such practical challenges have to be overcome by adequate technical and economical evaluation methods to select the promising options for conversion technology, plant location, plant capacity, logistics related activities and mix of renewable energy sources and system products to obtain a preliminary design for the plant. For obtaining the optimal design, more detailed optimization studies can be performed that are led from the preliminary design of the plant. A well designed energy system can be cost effective, meet economic constraints, use appropriate technologies, has a high reliability and can improve the quality of life in the areas that it serves.

Fig. 1 illustrates the allocation of the methods used in the studies surveyed in this paper. As demonstrated in the figure, various mathematical modeling and optimization methodologies have been employed for handling the problems related to the design and operation of renewable energy systems. In this regard, LP and NLP are widely used modeling techniques. The NLP models are mostly used with graphical interpretation and sensitivity analysis techniques. In a few studies, heuristic methods such as particle swarm optimization and genetic algorithm are used to solve the NLP models. Many energy systems optimization models with non-linear structure require heuristic algorithms as the solution methods. Heuristic methods such as simulated annealing and tabu search may provide fast and reliable solutions.

Fig. 1 depicts that simulation and simulation-based design methodologies are among the most preferred techniques because of their flexibility in adapting fluctuant system conditions and their ability to represent the real system structure more realistically. Life cycle analyses, geographic information systems-based methods and thermodynamic equations are other methods that are employed for optimal supply and allocation of renewable energy resources and technologies.

Most of the models applied for the energy system design work under different objectives such as satisfying minimum system costs and minimum level of harmful gas emissions, and a set of technological, economic, environmental, social and energetic constraints. Multi dimensionality of the sustainability goal and complexity of socioeconomic and biological systems make MCDM and

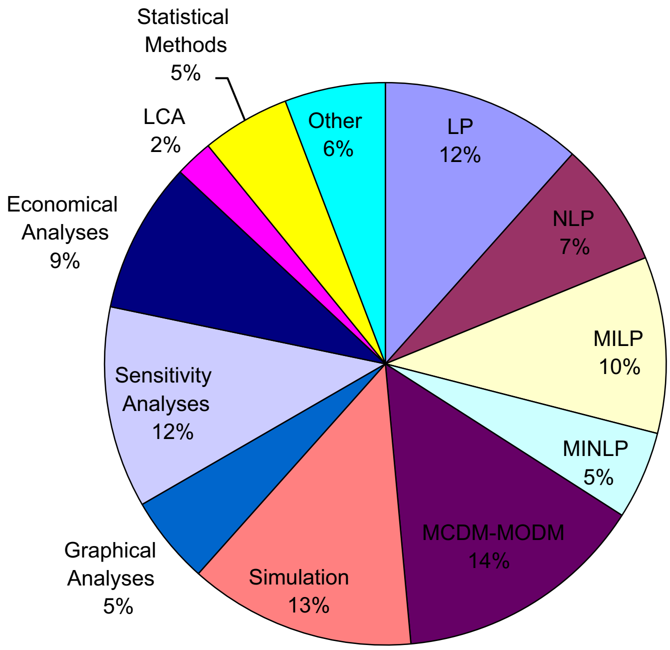

Fig. 1. Allocation of the methods used in the design studies.

MODM methodologies increasingly popular in decision making for sustainable energy systems because of their ability to integrate the multi-criteria and complex nature of these systems. Although goal programming is one of the most powerful MODM approaches in practical decision making which aims to minimize unwanted deviations from target values for objectives, this study reveals that it is rarely used in biomass to energy conversion systems design. Statistical methods (regression and correlation analyses, cumulative curves, least square method, factorial design) and economic analysis methods (cost analysis, payback period, net present value, internal rate of return) are used as alternative approaches to design renewable energy systems including biomass to energy conversion.

Uncertainty is the fact of life and business. As in almost all complex real life systems, there exist uncertainties and risks in renewable energy systems that have to be tackled in the investment planning phase. It is a challenging but required task to make decision under these uncertain and risky conditions in today's global and highly competitive energy markets. It is observed in this paper that the number of studies that considers these conditions in biomass to energy conversion system design is scarce. In this regard, fuzzy set theory and fuzzy modeling approaches can be utilized to provide the appropriate framework to describe and treat uncertainties.

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